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Studies on the effects of braking loads on a Railway Wheel

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Abstract. Indian Railways boasts as the superior modes of transportation in the country and it functions in all rural and urban networks including narrow, meter and broad gauges. Railway accidents due to mechanical failure of wheels are still considered with primary importance by research and development wing. Studies have revealed that the braking of tread zone of wheel results in non-uniform heating and creates severe stresses in railroad car wheels. The existing trend towards high speed trains and larger axle loads has created a need for a better understanding of the technology involved in designing of wheel. All the types of trains including freight and passenger, are generally braked using cast iron brake blocks which adds to the thermal loading on the wheel. Braking application for long time results in high temperatures on the wheel tread and the rim. Thermal loading has sufficient capability to not only initiate cracks but also increases the crack growth rate.

The focus of the paper is to study the effect of thermal interaction of Micro Alloyed AAR Class-B Grade Steel wheel and blocks during braking and after cool down. FE thermal analysis of a flat shaped wheel profile exposed to stop braking condition is simulated using Abaqus/CAE 6.13. Axle loads, rate of deceleration and brake sizes are taken as parameters to understand the effect of different running conditions on wheel tread surface. The results obtained show the effects of axle load, brake size and rate of deceleration on the peak temperature obtained on the tread surface. The analysis helped in determining the region of the rail wheel which is susceptible to failure due to steep temperature changes

Keywords: Rail wheel; Tread Braking; Thermal cracking; Finite Element Analysis; Contact Temperature.

1. Introduction

Indian Railways is one of the world's largest railway networks having 115,000 km of track over an extended route of 65,436 km and comprising 7,172 both rural and urban train stations. But almost 64% of this vast network is not yet electrified. Unlike in electrified systems, the locomotives are braked by conventional brake-block arrangement. Conventionally used Cast Iron brake blocks are prone to thermal deterioration. Almost 80% of the heat generated during braking due to friction between the mating wheel-block interfaces goes into the tread part of wheel. While the wheel surface is gaining heat due to braking, another phenomenon is taking place side by side which allows wheel to lose heat. Natural or forced convection of air allows wheels to lose heat simultaneously, making it susceptible to a cycle of continuous gaining and losing heat and thus leading to thermal fatigue damage. The schematic representation of the phenomenon is shown in Figure 1. Indian wagons have a different wheel web than the ones used in European and Australian continents and are designed to carry heavier axle loads, are braked more frequently and thus make this analysis important from an Indian perspective.



Researchers working in related areas have not attempted to explore on thermal analysis of rail wheels. Ekberg et al. [1] studied methods for estimating the residual lifetime of the S-shaped plate rail wheel configuration used across the globe, due to cyclic mechanical and thermal loads. They justified the importance of Rolling Contact Fatigue (RCF) Analysis over Classical Fatigue Analysis and also suggested various failure mechanisms of railway components.

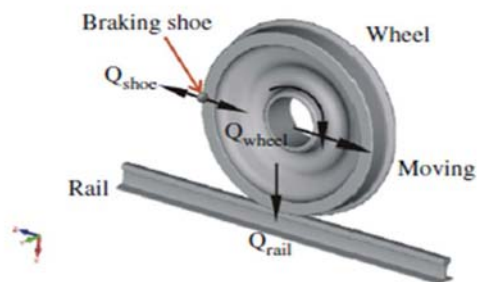


Figure 1. Wheel-Brake and Wheel-Rail interface

Based on the scientific understanding, they developed an engineering model for RCF which defined fatigue in terms of surface and subsurface defects. Peng et al. [2] studied growth of crack in an S-shaped wheel under thermal brake loading and calculated stress intensity factor of cracks using a semi-analytical solution technique that combines an analytical solution and a numerical algorithm to determine fracture strength of the material. The model developed stressed on the heat distributed around the circumference of the tread from friction during braking. Peng et al. [3] combined thermal braking and mechanical contact loads for damage tolerance analysis of a railway wheel and suggested methods to use heat transfer and fracture mechanics tools to predict thermal fatigue-induced cracks. For perfect thermal contact conditions between wheel-rail and wheel-brake interface, a simple semi-analytical numerical method for calculating the wheel tread temperatures was presented by Ertz et al [4] which further suggested an empirical relationship between wheel temperature and average temperature for the constant operating conditions and first contact of the cold wheel respectively could be developed and can lead to the possibilities of thermally induced phase transformations. Teimourimanesh et al. [5] presented a state of the art survey which gave an overview of design of tread braking system with special attention on braking capacity of the railway wheel. Newcomb [6] solved problem of 1-D heat conduction through infinite slab bounded by parallel planes and applied the solution to estimate temperatures during wheel braking at uniform deceleration. Deshpande et al. [7] investigated the problem of wheel tread defect in LHB coaches when the braking system was changed from tread braking to disc braking and concluded that disc brakes are responsible for larger heat generation at the wheel brake interface due to larger torque causing the wheel to spall. Srivastava et al. [8] presented a review of effects of thermal loads on wheel rail contacts and suggested that thermal loads must be considered alongside the evolved defects to completely understand the dynamic material response. Naeimi et al. [9] used FEA to present a coupled thermo-mechanical analysis of wheel-rail contact and evaluate temperature rise and stresses in the contact zone.

2. Thermal Load

When brakes are applied for prolonged duration of time, it results rise in temperature of the tread and rim and is called thermal loading. It has the ability to commence cracks and increase its growth rate. Speed of a train running on a track can be reduced either by Stop Braking or Drag Braking. Stop Braking is the continuous application of brakes till the train is brought to rest. Stop Braking tends to produce large temperatures on the tread surface in a short duration of time. Stop Braking depends on the rate of deceleration. Normally Indian trains decelerate at the rate of 0.5 m/s^2 to 1.2 m/s^2 which may increase up to 1.5 m/s^2 in case of emergency brakes. The paper aims to find the effect of increasing the rate of deceleration on the temperatures attained over the tread surface. Drag Braking or downhill

braking is used to limit the speed of train to a particular value while running down a slope. Potential increase in train speed is detained by applying brakes at constant pressure for longer time. Though drag brakes may be applied for a larger duration, say hours, its overall effect over the wearing of tread surface is less compared to stop braking. Therefore, effect of drag braking is beyond the scope of this paper.

Energy required to stop the vehicle is a summation of potential, kinetic and rotational energy. Potential energy is the energy inherited or lost by the vehicle by virtue of its position at rest on hill or at a height. Assuming train to be moving on a leveled track, potential energy will be zero. Kinetic energy is the energy required to bring the vehicle to rest whereas rotational energy is the energy required to reduce the motion of rotating parts to zero and is assumed as 3% of the kinetic energy of the vehicle, based on earlier reports in similar fields. For a wagon with average axle load 10 tonnes per wheel running at 100 km/h if brought to rest at deceleration rate of 0.5 m/s^2 , will mean a braking time of 55.5 seconds i.e for almost 56 seconds the tread surface will be exposed to a continuous heat source. In 56 seconds, the train will cover a braking distance of 770 m with the braking energy 3.97 MJ per wheel and initial power of 71.43 kW per wheel.

Now in order to estimate the one-stop temperature rise in the wheel disc interface, an assumption to the location of dissipation of the braking energy has to be made. In the beginning, maximum rise in temperature is observed in the disc; however the disc is rapidly cooled by surrounding components and the natural convection of stream of air. The calculation is done with the assumption that 90% of the total energy generated is retained by the disc. Heat flux into the sides portion of the disc is calculated using the equation in [4]:

$$q = \frac{4P}{\pi(D^2 - d^2)} \quad (1)$$

Temperature rise in a single stop braking is determined using equation:

$$T_{max\theta} = \frac{0.527q\sqrt{t}}{\rho ck} + T_{amb} \quad (2)$$

Brake material is assumed to be cast iron with density as 7250 kg/m^3 , specific heat capacity 500 J/kg/K and thermal conductivity 58 W/m K .

3. Finite Element Model

In order to conduct the FE thermal analysis of the 920 mm diameter flat shaped of high carbon steel, AAR grade B wheel profile model experiencing stop braking is considered. Only one-half of the wheel is modelled first considering the axial symmetry [10]. The temperature distribution obtained is found to be in complete agreement with the axisymmetric model for the S-shape rail wheel profile by Peng et al [11].

The resultant mesh created using Abaqus®, was with 38060 eight noded linear heat transfer brick element and 44240 nodes. To model the thermal effect of brakes on the interface, a fine mesh in 0.1584 m^2 contact region was used in the wheel-brake.

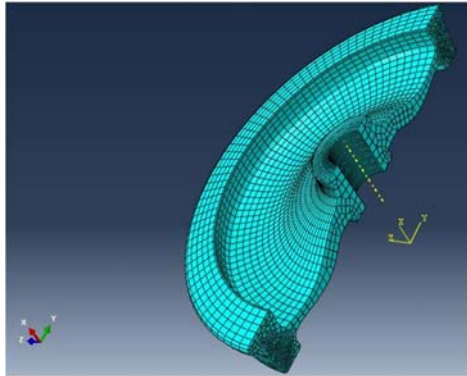


Figure 2. The 3-D mesh of a 920 mm Railway Wheel

4. Material Properties

The material model is assumed to be equivalent to Microalloyed AAR Class B wheel steel and is extracted from Peng et al [11].

Table 1. Material properties of wheel

Yield Strength	360 MPa
Young's Modulus	206 GPa
Poisson's Ratio	0.286
Density	7870 kg/m ³
Specific Heat	490 J/kg °C
Coefficient of Thermal Expansion	14×10 ⁵
Thermal Conductivity	47.5 W/°C m
Free Convection Heat Transfer coefficient	25×10 ⁶ W/ °C m ²

5. Transient Heat Transfer Analysis

Figure 3 represents the temperature attained in the tread region of the railway wheel at different times under stop braking conditions. The train was assumed to be running at a speed of 100 kmph when stop brakes were applied to stop the train in 770 m in duration of 56 seconds. Figure 4. shows the temperature profile obtained for the stop braking case for a duration of 56 seconds. The maximum temperatures of 222 °C are attained in the tread region of the wheel web.

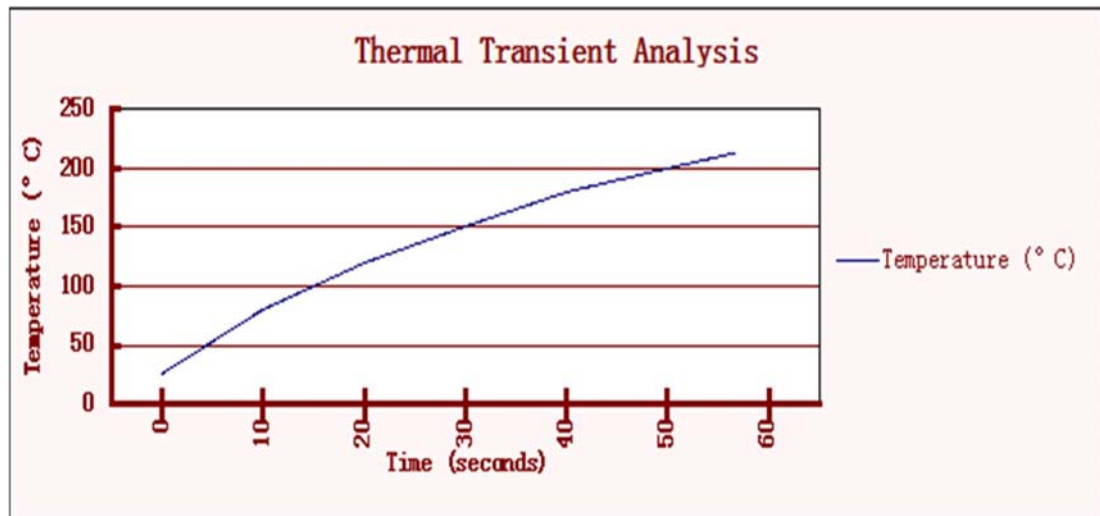


Figure 3. Results of the transient analysis for the maximum temperatures attained in the tread portion of the wheel vs the braking time under stop braking application (average power 71.43 kW per wheel and duration 56 seconds).

6. Results and Discussion

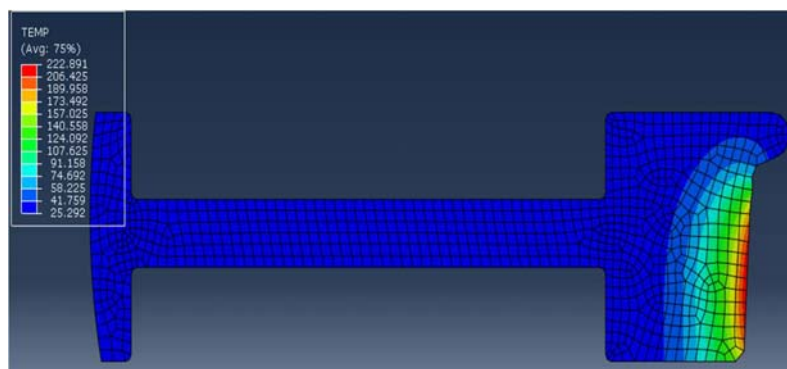


Figure 4. Temperature profile obtained in a flat web shaped railway wheel under stop braking conditions for a duration of 56 s by axisymmetric analysis

With an aim to show the effects on the thermal stresses of a Flat-shape plate railway wheel under braking load, various parameters associated with the locomotive in motion were varied and corresponding influence on the temperatures is estimated.

6.1 Temperature distribution for stop braking by varying the rate of deceleration

Figure 5 compares the results obtained when rate of deceleration is varied from 0.5 m/s^2 which is the standard rate of deceleration to 1.5 m/s^2 for the case of emergency braking. The maximum temperature obtained in the tread region for a locomotive brought to stop from a speed of 100 kmph was around 220°C for normal braking whereas temperatures as high as 415°C were obtained for emergency braking. Approximately 200% more increase in temperature is observed for more severe cases of braking.

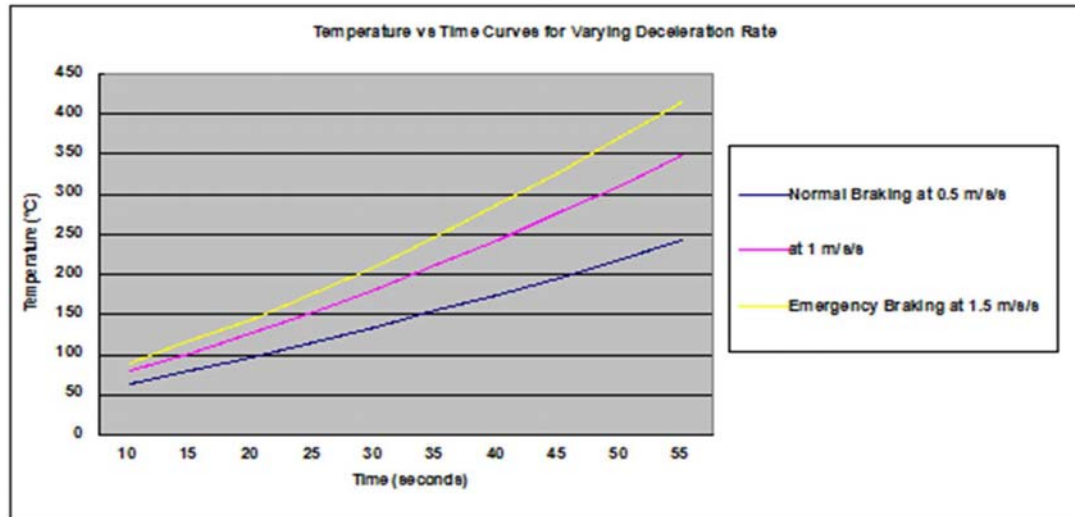


Figure 5. Results of the transient analysis for the maximum temperatures obtained on the wheel tread surface by varying the rate of deceleration from 0.5 m/s² standard rate of deceleration to 1.5 m/s² for the case of emergency braking.

6.2 Temperature distribution for stop braking by varying the axle load capacity

Figure 6 compares the results obtained when tonnage capacity of axle is varied from 15 tonnes which is the standard capacity of a passenger train i.e 7.5 tonnes per wheel to 25 tonnes for a goods train. The maximum temperature obtained for the train having a capacity of 25 tonnes was 390 °C which was approximately 170 % more than the temperatures obtained for the passenger train running under similar conditions. Figure 8 shows similar relationship between heat flux against the time for the same running conditions as above for varying axle loads.

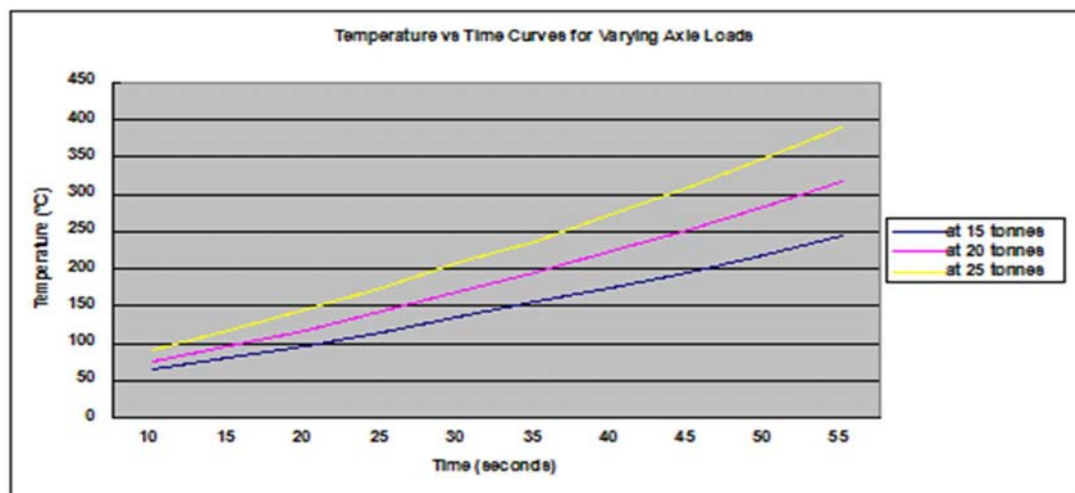


Figure 6. Results of the transient analysis for the maximum temperatures obtained on the wheel tread surface by varying the axle loads from 15 tonnes capacity of the normal passenger locomotive to 25 tonnes capacity of goods and freight wagon.

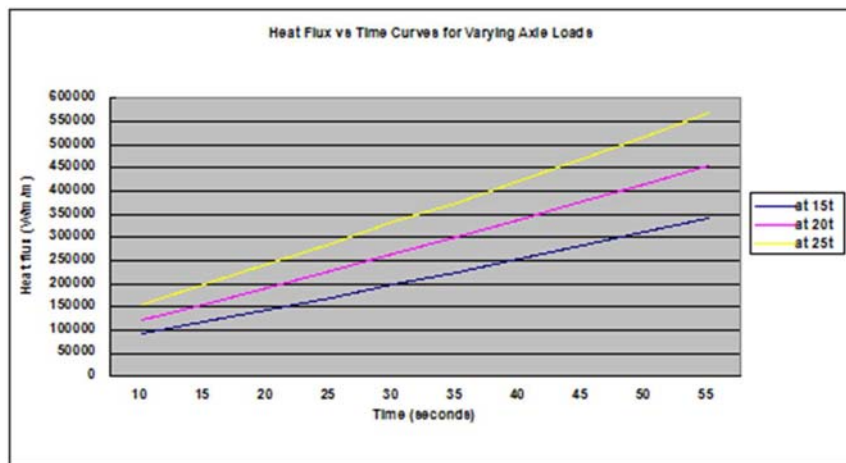


Figure 7. Heat Flux against Time curves for varying axle loads

6.3 Temperature distribution for stop braking by varying Wheel-Brake Contact Area

Figure 8 shows the results of changing the Brake contact area by varying the contact angle. Indian railways use brakes of varied contact angles depending upon the maximum speed and load bearing capacity of the locomotive. Braking is accomplished rubbing the brake blocks varying from 0.1584 m^2 to 0.1853 m^2 against the wheel tread surface. Analysis showed 20 to 30 % change in maximum temperature for a change in the contact angle.

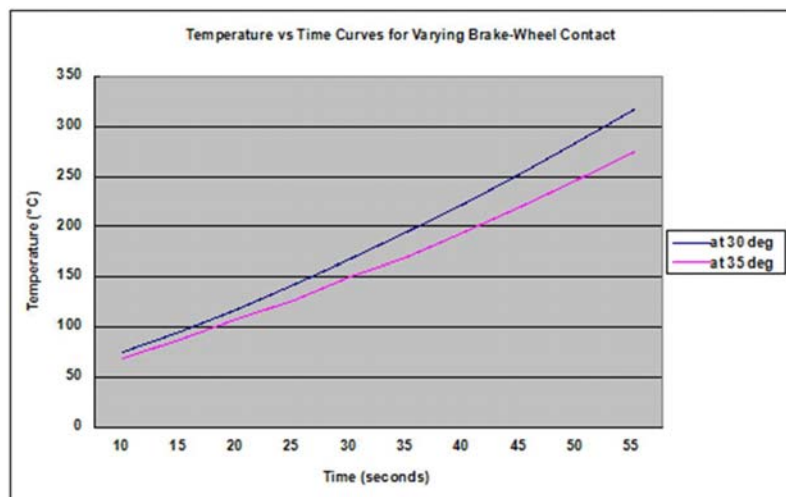


Figure 8. Results of the transient analysis for the maximum temperatures obtained on the wheel tread surface for Brake contact angle of 30° and 35°

7. Conclusion

The studies showed how transient thermal analysis can be used to predict the effect of different parameters of a running train on the maximum temperatures and heat flux obtained on the tread surface. Thus the effect of change in running conditions can be determined. The work indicated that increasing the rate of deceleration has a major impact on the temperatures attained and therefore braking should neither be hard nor frequent. Peak temperature values almost double if the trains are

brought to rest under emergency braking. Considerable changes in temperatures are also observed with a change in Wheel-Brake contact area and load bearing capacity of the locomotive. Issues other than large wear observed in the study like influence of climate, relation between wear and fatigue and rail chill have not been considered. This forms the part for future studies.

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